

# Practical implementation of spectrum splitting for solar cells

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**ABSTRACT:** In the past decade, a number of inventions have been patented, describing all a different technology to achieve spectral beam splitting for solar cells. This paper describes a novel light splitting device, that could solve some of the additional problems encountered by previous inventions, such as no overlap in photon frequencies, no moving parts, lightweight and lower influence by tracking errors. The practical optical efficiency of our device was calculated using available materials. Although there is still room for improvements, a calculated practical optical efficiency of 66% is reached.

**Keywords:** Chromatic Dispersion, Concentrators, Optical Devices, Optical Losses, Solar Cell Efficiencies

## 1. PRESENTATION

Hereby we present a new practical implementation of spectrum splitting for solar cells. The device is a prism-like body. The size can be chosen freely, keeping in mind that the photon absorption is a function of the traveling length. A smaller device absorbs less photons, increasing the efficiency. For example, if the concentrator lens would be  $1 \text{ m}^2$ , with a concentrating factor of 1000, the input surface is  $1000 \text{ mm}^2$  (or a square of 31.6 mm by 31.6 mm) and the average length of the device would be around 123 mm. The idea behind this device, shown in fig. 1, is that it uses a parallel bundle of photons, whether or not concentrated. This parallelized bundle of photons enters a highly dispersive medium which is designed with surfaces, on a certain angle, namely the total reflection angle for photons with a energy level equal to the bandgap of the PV cell installed on the next stage. Thus splitting the light, allowing photons with certain energy levels to pass through a certain surface, and totally reflects the photons with other energy levels to the next surface.

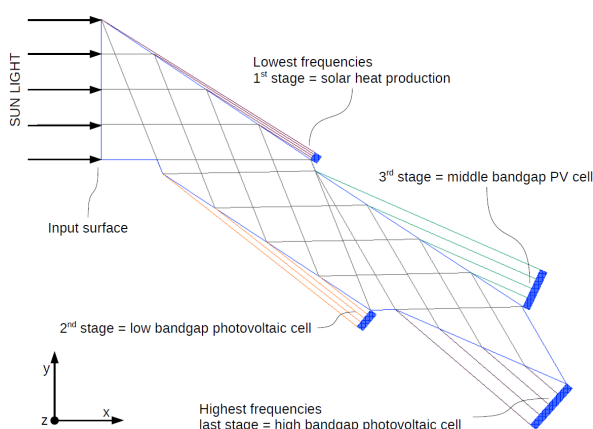


Fig. 1. Idea for a new device. Drawing on scale to the input surface.

## 2. INTRODUCTION

Nowadays, triple (or multi) junction solar cells are used in concentrated photovoltaic systems. The advantage of multi junction photovoltaic cells is that every junction converts a part of the solar spectrum in such a way that the efficiency of the multiple junctions combined is greater than

the efficiency of single junction solar cells. Disadvantages of (non mechanically stacked) multi junction solar cells is the need of matching the lattice constant and the current for every junction. Another disadvantage is that, the energy losses within every junction add up to the increase of temperature of the whole cell, not only decreasing the efficiency of every junction and limiting the allowed concentration level, but also contribute to the thermal stress[1] CPV has to endure. Recently the U.S. Defense Advanced Research Projects Agency (DARPA) started the Very High Efficiency Solar Cell (VHESC) program[2], [3].

Even though without using multiple junction PV, spectral beam splitting techniques are also interesting for usage in combined photovoltaic - thermal energy systems or in single junction PV modules by reducing the heat buildup within the junction to improve the overall efficiency[4]. Many inventors already came with solutions to overcome one or more of the above stated problems. Such as inventors Joseph Dettling[5] fig. 2.a) and Diana H Kim[6] fig. 2.b), who came with a solution by splitting up the light spectrum using a prism. Or Jay P. Penn[7] fig. 2.c), who invented the high concentration spectrum splitting solar collector and Moshe Einav[8] fig. 2.d) who came with an alternative using a refraction array with at least one refraction sub-array. The advantage of their invention is the improvement of efficiency by lowering the temperature, improve the cool-ability of the cells and also matching the current and/or lattice constant isn't necessary. Inventor Detlef Schulz[9] fig. 3.a) and inventors Joshua Monroe Cobb and John H. Bruning[10], [11] fig. 3.b) came with an alternative solution by splitting up the light spectrum into spectral bands using a thin film of semi transparent material, a coated mirror concentrator or a dual (one semi transparent) mirror concentrator. The advantage of these inventions are similar to the advantages of the previous described invention, but they use a thin film/layer instead of a prism-like light splitter. A good review on more spectral beam splitting techniques has been described by A. G. Imenes and D. R. Mills[12].

## 3. COMPARISON WITH ALTERNATIVES

Next to the advantages of the previous inventions, as explained in the Introduction, there are some disadvantages that are overcome by in this paper presented device.

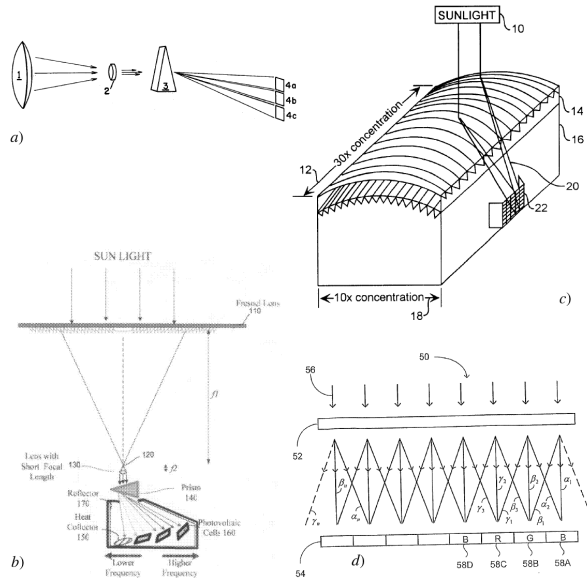


Fig. 2. Invention a) Joseph Dettling[5], b) Diana H Kim[6], c) Jay P. Penn[7], and d) Moshe Einav[8].

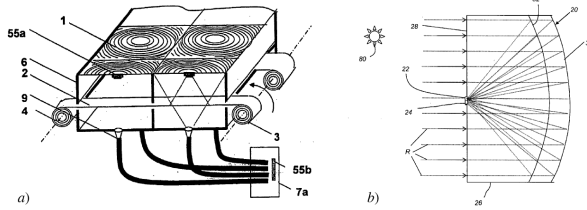


Fig. 3. Invention a) Detlef Schulz[9], and b) Joshua Monroe Cobb and John H. Bruning[10], [11].

#### A. Prism-like spectrum splitters

By using prisms[5], [6], [7], the mismatch and overlap of photon frequencies on the different PV cells will be the major disadvantage. Because of this, solar tracking errors have an important impact. And by placing the different PV cells close to, or next to, each other[5], [6], [7], [8], the excessive heat of one cell, will increase the temperature of the neighboring cells. Although the total area is increased, which improves the cool-ability compared to normal CPV cells.

#### B. Thin film/coating-like spectrum splitters

The main disadvantage is that the thickness of the coating[10], [11] may change due to temperature fluctuations and for thin film[9] the thickness may change due to temperature fluctuations, stretching and wear of the thin film.

#### C. Our spectrum splitter

The light splitting device presented here has no moving part, making it robust. Fairly small, which makes it lightweight and cheap to make. But above all, only solar tracking errors around the Z-axis (see fig. 1) have a small influence on the incident angle, making the light splitter less efficient, but still useful. As long as the solar tracking errors around the Y-axis is smaller than  $20^\circ$  ( $0.35$  [rad]), this tracking error will have no effect on the efficiency of our light splitting device, it only has an effect on the light distribution after the spectrum splitter.

TABLE I  
CONSTANTS OF DISPERSION. DATA SHEETS OBTAINED FROM SCHOTT [13] AND VALID FOR WAVELENGTHS FROM THE NEAR UV TO  $2.3\mu\text{m}$ .

	SF57HHT	N-BK10	LF5	LLF1
$B_1$	1.81651371	0.888308131	1.52481889	1.21640125
$B_2$	0.428893641	0.328964475	0.187085527	0.13366454
$B_3$	1.07186278	0.984610769	1.42729015	0.883399468
$C_1$	0.0143704198	0.00516900822	0.011254756	0.00857807248
$C_2$	0.0592801172	0.0161190045	0.0588995392	0.0420143003
$C_3$	121.419942	99.7575331	129.141675	107.59306

#### 4. METHODOLOGY

The remaining question is, however, how will our light-splitting device 'work' in reality? To calculate the photon throughput, materials were chosen from Schott [13] and the bandgaps chosen are 1.83eV, 1.34eV and 0.89eV [14], but other dispersive media and photovoltaic materials are also possible. The effect of temperature on refractive index [15], [16] was ignored during the simulation, as well as the reflection on the first surface, where photons enter the main medium, as well as the absorption inside the media. The efficiency of photon throughput is also dependent on the input spectrum, whether AM0, AM1, AM1.5 or something else is used. Calculations have been done for AM0 and AM1.5d with values obtained from [17]. First the materials were selected. SF57HHT as the base material, N-BK10 for stage 1, LF5 for stage 2, LLF1 in stage 3 and again SF57HHT for stage 4. These materials were chosen because of their low absorption rate for the wavelength range of interest and high dispersion factor for SF57HHT. The refraction index can be calculated using Sellmeier's dispersion formula (see equation 1[13]), using the constants of dispersion found table I. Secondly the efficiency of photon throughput was calculated using the optimal theoretical total internal reflection angle that corresponds to the chosen initial bandgaps. Next the angle of the different stages was changed, allowing Matlab to find the most optimal refraction angle to get the best photon throughput efficiency.

$$n^2(\lambda) = 1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3} \quad (1)$$

#### 5. RESULTS AND DISCUSSION

Please note that the results shown in table II are optimized for maximum photon throughput and do not take quantum efficiency into account. In table II, 'U.' stands for Useful, 'P.S.' for Previous Stage(s), 'N.S.' for Next Stage and 'N.U.' for Not Useful. Useful (U.) being the amount of photons useful for the stage it passes through. E.g. for stage 3, all photons with an energy level between 1.34eV and 1.83eV should be directed to the middle bandgap PV cell. Previous Stage(s) (P.S.) represents the amount of photons with energy levels lower than the bandgap energy of the junction present at the particular stage (e.g. for stage 3, all photons with an energy level lower than 1.34eV). Not only would these photons be useful for the previous stage, they also only contribute to the added heat, decreasing the efficiency of the cell. Next Stage (N.S.) represents the amount of photons with energy levels higher than the bandgap energy of the junction present at the next stage (e.g. for stage 3, all photons with an energy level higher than 1.83eV). Although these photons do contribute to the electrical energy production of the cell, it would have been more efficient if these photons would

TABLE II  
RESULTS FOR CALCULATIONS WITH MEDIUM 0 AND 4 = SF57HHT, MEDIUM 1 = N-BK10 MEDIUM 2 = LF5 AND MEDIUM 3 = LLF1 [13] (Abbreviations : U. : Useful, P.S. : not useful, should have been send to the Previous Stage(s), N.S. : useful, but should have been send to the Next Stage and N.U. : Not Useful)

	stage 1		stage 2			stage 3			stage 4		total	
	U.	N.S.	P.S.	U.	N.S.	P.S.	U.	N.S.	P.S.	U.	U.	N.U.
AM0	3.11%	0%	6.47%	6.33%	0%	13.13%	11.82%	0%	24.33%	34.82%	56.08%	43.92%
AM0 <sub>optimized</sub>	5.00%	1.51%	6.50%	8.30%	2.54%	10.31%	12.80%	1.39%	18.05%	33.61%	65.15%	34.85%
AM1.5d	2.31%	0%	5.08%	6.61%	0%	12.10%	13.76%	0%	26.09%	34.06%	56.74%	43.26%
AM1.5d <sub>optimized</sub>	3.84%	1.55%	4.99%	8.31%	2.68%	9.85%	15.65%	2.23%	18.91%	31.99%	66.25%	33.75%

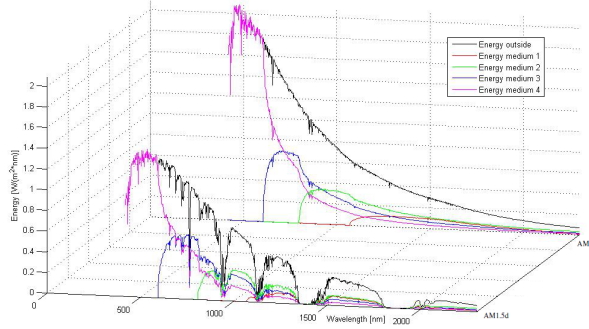


Fig. 4. Results: photon throughput in every medium for AM0 and AM1.5d.

reach the next stage, with a PV cell with higher bandgap. So the 'useful' in the 'total' column is the sum of all 'U.' and 'N.S.', while the Not Useful (N.U.) column represents the total losses (sum of P.S.). As seen in table II, the maximum optical efficiency of our device reaches 66%. This efficiency can further be improved if a more disperse material is used as base material.

## 6. CONCLUSION

Many inventors worked on spectral beam splitting technology. In this paper we presented a new device that overcomes some of the practical problems previous inventions may encounter, such as no overlap in photon frequencies, no moving parts, lightweight and lower influence by tracking errors. After selecting the best available materials, the practical optical efficiency was calculated to be 66%. This, however, without taking into account other losses such as initial reflection and absorption losses. The efficiency of this device could greatly be improved if more dispersive materials (compared to SF57HHT) could be made, while absorption losses can be reduced by making the device smaller.

## 7. ACKNOWLEDGEMENT

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## REFERENCES

- [1] N. Bosco, T. Silverman, and S. Kurtz, "Modeling thermal fatigue in cpv cell assemblies," *Photovoltaics, IEEE Journal of*, vol. 1, no. 2, pp. 242–247, oct. 2011.
- [2] A. Barnett, C. Honsberg, D. Kirkpatrick, S. Kurtz, D. Moore, D. Salzman, R. Schwartz, J. Gray, S. Bowden, K. Goossen, M. Haney, D. Aiken, M. Wanlass, and K. Emery, "50% efficient solar cell architectures and designs," in *Photovoltaic Energy Conversion, Conference Record of the 2006 IEEE 4th World Conference on*, vol. 2, may 2006, pp. 2560–2564.

- [3] A. Barnett, D. Kirkpatrick, C. Honsberg, D. Moore, M. Wanlass, K. Emery, R. Schwartz, D. Carlson, S. Bowden, D. Aiken, A. Gray, S. Kurtz, L. Kazmerski, M. Steiner, J. Gray, T. Davenport, R. Buelow, L. Takacs, N. Shatz, J. Bortz, O. Jani, K. Goossen, F. Kiamilev, A. Doolittle, I. Ferguson, B. Unger, G. Schmidt, E. Christensen, and D. Salzman, "Very high efficiency solar cell modules," *Progress in Photovoltaics: Research and Applications*, vol. 17, no. 1, pp. 75–83, 2009. [Online]. Available: <http://dx.doi.org/10.1002/pip.852>
- [4] G. Tina, F. Cosentino, and G. Notton, "Effect of thermal gradient on electrical efficiency of hybrid pv/t," in *Effect of Thermal Gradient on Electrical Efficiency of Hybrid PV/T*, no. ISBN: 3-936338-26-4. Proc. PVSEC, September 2010, pp. 4119–4124.
- [5] J. R. Dettling, "High efficiency converter of solar energy to electricity," American Patent US1975 611 454A, May, 1977.
- [6] D. H. Kim, "Concentrator-based photovoltaic system by parabolizing and splitting the high intensity light," American Patent US 2009/0065 044 A1, March, 2009.
- [7] J. P. Penn, "High concentration spectrum splitting solar collector," American Patent US 6,469,241 B1, October, 2002.
- [8] M. Einav, "Stationary solar spectrum-splitting system and method for stimulating a broad-band photovoltaic cell array," Israel Patent WO 2009/122 414 A2, April, 2009.
- [9] D. Schulz, "Process for the energy conversion of solar radiation into electric power and heat with colour-selective interference filter reflectors and a concentrator solar collector with colour-selective reflectors as an appliance for applying this process," German Patent US 2009/0014 053 A1, January, 2009.
- [10] J. M. Cobb and J. H. Bruning, "Light collector and concentrator," American Patent US 2007/0 137 691 A1, June 21, 2007.
- [11] —, "Apparatus for obtaining radiant energy," American Patent US 2007/0 107 769 A1, May 17, 2007.
- [12] A. G. Imenes and D. R. Mills, "Spectral beam splitting technology for increased conversion efficiency in solar concentrating systems: a review," *Solar Energy Materials and Solar Cells*, vol. 84, no. 1-4, pp. 19–69, 2004, international Solar Energy Society World Congress 2003.
- [13] Schott. [Online]. Available: <http://www.schott.com/>
- [14] M. Stan, D. Aiken, B. Cho, A. Cornfeld, J. Diaz, V. Ley, A. Korostyshevsky, P. Patel, P. Sharps, and T. Varghese, "Very high efficiency triple junction solar cells grown by movpe," *Journal of Crystal Growth*, vol. 310, no. 23, pp. 5204–5208, 2008.
- [15] T. Mikami, T. Okamoto, and K. Kato, "Sellmeier and thermo-optic dispersion formulas for rbtio<sub>4</sub>," *Optical Materials*, vol. 31, no. 11, pp. 1628–1630, 2009.
- [16] L. Deng, X. Gao, Z. Cao, W. Chen, Y. Yuan, W. Zhang, and Z. Gong, "Improvement to sellmeier equation for periodically poled linbo<sub>3</sub> crystal using mid-infrared difference-frequency generation," *Optics Communications*, vol. 268, no. 1, pp. 110–114, 2006.
- [17] *Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface*, ASTM Std. G173 - 03(2012).